Applications of advanced clocks for space navigation, and communication[1]

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Abstract

Precision clocks and frequency standards are widely used in communications and navigation systems. In navigation, time and frequency references are the parameters that contribute to the ultimate accuracy of position location. While clocks and frequency standards are widely used in commercial, military, and NASA satellites, the emergence of new requirements in all these arenas have pointed to the need for new classes of standards with improved performance. In particular, the success of Global Positioning System (GPS) in numerous communications and navigation applications has already led to the need for small, high performance clocks to improve the present capabilities. Furthermore, many future spacecraft systems in autonomous and or cluster configurations require advanced clocks. Applications of advanced clocks will also be crucial for position location on Mars, where it is expected that a large number of probes will be deployed, and will be monitored independently. In this paper a general discussion of the clock applications will be followed by a description of advanced clocks, and projection for their anticipated future applications.

Introduction

Amongst the myriad applications of clocks and frequency standards in science and technology, communications and navigation are two of the most important. With respect to communications, every signal in a communications system is derived from or compared to a reference signal generated from a frequency reference, and so frequency standards play an enabling role in these systems. In the case of space communications systems, extremely coherent signals are often required which can only be derived from the highest performance references. Clocks also represent the enabling technology for navigation, and are used to determine the location of spacecraft in its trajectory.

Future applications in space communications and navigation, including autonomous, or multi-element systems, can benefit from the type of atomic clocks currently under

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development through NASA support. This is particularly true for Mars missions where constellation of multi-sensor and multiple spacecraft are being planned. In this paper the applications of clocks to navigation and communications in space will be described, together with a discussion of the technical background of atomic clocks currently under development for NASA.

While there is a somewhat subtle difference between atomic "clocks" and "frequency standards", for the purpose of this paper the two terms will be used interchangeably. This will not modify the content for the general reader, and will only be of interest to the experts in time and frequency.

Clock Applications

Historically, the major application of clocks in space missions consisted of navigation. In its simplest form, measurement of the round-trip time of flight of a signal from the ground to spacecraft and back provides the ranging information. This information is typically quite accurate, even with lower performance clocks. But when the angular location is needed, the service of atomic clocks is required. This is because the angular position of the spacecraft may be determined using Very Long Baseline Interferometry (VLBI) techniques utilizing a radio map of the sky. This and similar approaches require highly stable clocks. For example, if the stability of the clock is on the order of a part in 10^{13}, the determination of the location of spacecraft at Jupiter distance will be uncertain by about 300 km. The determination of the velocity of the spacecraft with Doppler tracking also usually requires high stability frequency standards (in the 10^{15} range), depending on the needed accuracy. If the orbit determination requirement is at a one meter range for an interplanetary mission, clock stability in excess of 10^{15} may be required.

The advent of the Global Positioning Satellite system (GPS) has made the applications of clocks for navigation quite widespread. The basis of GPS navigation is the availability of an atomic clock onboard each satellite whose time information is combined with the knowledge of the location of GPS satellites to determine the location of a GPS receiver. This approach is different from VLBI and has been successfully applied to terrestrial navigation with great success. It is also being applied to a selected number of earth orbiting satellites. The success of the GPS navigation, now requiring relatively simple and inexpensive receivers, naturally has prompted investigations to apply similar techniques to other space missions. In particular, the application of a GPS style positioning scheme for Mars, where constellations of rovers, probes, and stations are being planned, appears to hold the promise for great efficiency of operation.

A possible approach in using the GPS style navigation on Mars is to place a good atomic clock on one, or preferably two, orbiters with another clock placed on a stationary lander. This configuration, combined with ground support can help determine the location of every lander, rover, and probe to centimeter range accuracy. The receivers required for detecting the orbiter signals will be simple and very small, so that even smaller probes may be located. At any case, the atomic clocks are the enabling technology for such a scheme; the problem of the size and power requirements of receivers and antennas are within the current capabilities of micro-electronics technology.

A similar scheme may also be applied for the case of cluster missions. Here a mother ship in the cluster will carry a precision clock, and the other members of the cluster will carry the GPS style receivers. Each spacecraft in the formation then may be located precisely with respect to the mother ship, whose position with respect to the ground is in turn determined precisely using the onboard clock and a one-way (downlink only) communication link.

Atomic clocks will also enable communications for autonomous spacecraft of the future. Autonomous spacecraft are envisioned to be left un-tracked and without earth based uplink corrections to arrive at a destination, perform science functions, and beam back the data after the completion of the mission. This approach greatly reduces the cost of spacecraft tracking and communication for the period of the mission life, which for some of the currently planned missions could be ten years or longer. The success of autonomous missions naturally depends on the availability of sophisticated intelligence onboard to recognize the need for an action, and take appropriate steps. This function strongly depends on the timing capability onboard which is key to the execution of pre-programmed tasks. Accurate timing is also required to ensure that ground stations will be operating when data is transmitted by the spacecraft at the end of its mission. Thus the more sophisticated the autonomy functions, and the longer the period of autonomy, the higher the requirements for the timing capability will be. It is then clear that for some of future autonomous missions the service of atomic standards may be required.

Technical Background

In this section a general discussion of the physical and operational basis of atomic standards is presented. Atomic standards are superior to man-made composite resonators, e.g., quartz crystal or cavity resonators, by the inherent indistinguishbility of one atom from the next, for example, one cesium atom from the other. This feature ensures that atoms as clocks can be more reproducible in their operating frequency than any macroscopic crystal or cavity resonator ever constructed, since no two such resonators will ever be exactly identical.

Atomic frequency standards are based on the simple quantum mechanical relation between the energy difference of two atomic energy levels and the frequency of the photon connecting these levels in an emission or absorption process: $\Delta E = h\nu$. Here ΔE is the energy separation of the two levels, h is Planck's constant and ν is the frequency of the photon. Based on this relation a comparison of the frequency of an external oscillator with the frequency of a photon connecting two atomic energy levels can lead to a frequency standard.

In their operation, atomic frequency standards transfer the stability of an atomic resonance to steer a local oscillator (LO), which in the case of microwave standards is usually a 5 MHz quartz crystal oscillator. The local oscillator is characterized with a stable frequency typically over periods of from 1 to 100 seconds, but its frequency drifts or otherwise degrades for longer time spans. Outlining the procedure used to correct such frequency changes in an LO reveals some of the desirable properties of an atom to be used as the basis for an atomic clock. For example, Cesium and Rubidium atoms, and mercury ions are attractive because their large resonance frequency is more sensitive to variations in LO frequency changes. Thus a frequency step in the LO of 5×10^{-13} corresponding to 2.5 μHz at the 5 MHz operating frequency will be multiplied to 20 mHz at the $\nu_0 = 40.5$ GHz mercury resonance but only to 0.7 mHz at the ν_0=1.4 GHz hydrogen resonance. With equal frequency discrimination at the atomic resonance the higher operating frequency will clearly steer the LO in a more stable lock. Frequency discrimination at the atomic resonance is determined by the sharpness of the atomic resonance line, $\delta\nu$, together with SNR achieved in the measurement of this line. These three parameters determine the stability of the LO when locked to the atomic resonance; stability = $\delta\nu/\nu_0$/SNR. Since SNR increases as square root of the measurement intervals for white noise processes such as the photon or atom counting in detecting the atomic transition, we find that stability = $1/(Q \times SNR \times \sqrt{\tau})$ where we have introduced the line quality parameter, $Q = \nu_0/\delta\nu$.

The improvement in frequency stability gained through averaging over longer time intervals breaks down, however, when inevitable changes in the atomic environment lead to small changes in the atom's resonant frequency. It is of great practical importance, however, that atomic transitions exist which are far more immune to changes in the atomic environment than any man-made oscillator. Nevertheless, isolation from environmental perturbations drives the technology and development of all atomic frequency standards. The choice of the atom to be used as the clock determines the sensitivity to external perturbations and how much shielding from these environmental changes will be necessary to reach a given level of stability. Because the shielding adds a great deal to the bulkiness and complexity, it is especially important for space borne clocks, where low mass and high reliability are paramount, that the standard be inherently immune to environmental changes so that only relatively modest shielding is required.

The sensitivity of the atomic resonance frequency to temperature variations determines the complexity of the thermal engineering and regulation necessary to shield against thermal perturbations in the deep space environment. This sensitivity is set by the second order Doppler shift of the atoms in thermal motion at temperature T and the fractional frequency shift which is given by $d\nu/\nu=-3k_BT/(2mc^2)$ where k_B is Boltzmann's constant and mc^2 is the rest mass of the atom. For a fixed temperature change Hg^+ ions shows only 0.5% of the corresponding frequency shift of hydrogen atoms. In the case of laser cooled cesium and rubidium standards, the second order Doppler is rendered practically negligible; the atoms are as cold as a few micro-Kelvin due to their interaction with the laser light. Thus thermal regulation would be much less demanding for these standard. For science applications where ultra-high performance is required, careful thermal designs for cesium, for example, would be required to reduce the influence of more subtle effects, such as a shift of the energy levels due to interaction with the environmental Balck Body radiation.

Another large source of perturbation to the atomic resonance frequency is the variations in the ambient magnetic field. The atomic physics of the magnetic interaction within the ground state hyperfine levels used for the clock transition shows that the fractional frequency sensitivity to a magnetic field change experienced by the atom is proportional to H_0/ν_0^2, where H_0 is the strength of the applied magnetic field at the location of the atom, and ν_0 is the frequency of the atomic transition used for clock operation. Because mercury has a 40.5 GHz atomic splitting it will be 20 times less sensitive than cesium, 35 times less than rubidium, and 840 times less than hydrogen for the same operating field H_0. Atoms with large clock splitting require less magnetic shielding to reach the same insensitivity to ambient field variations.

The stability obtained with atomic frequency standards is a result of success with which the above steps are implemented. Different approaches have produced different instruments, the most notable of which are the rubidium standard, the cesium beam standard and the trapped ion standard. In the case of the laser cooled cesium and rubidium clocks their long term stability, reproducibility, and accuracy make them the instrument of choice for time keeping and for applications where very long term stability is required.

Conclusion

The development of the first accurate clock by John Harrison in the mid 1700's revolutionized the science of navigation, and enabled the Royal Navy to lead all nations in the exploration of the earth. Some 250 years later, atomic clocks are poised to lead NASA's exploration of the solar system and the universe into the new millenium. As we cross the threshold to the 21st century, precise navigation of NASA's piloted and robotic crafts, in space trajectories and on the surface of Mars and other bodies in the solar system, will open new vistas into our world. Atomic clocks and frequency standards will continue to enable this quest.